Light Dark Matter Targets for Accelerator Searches

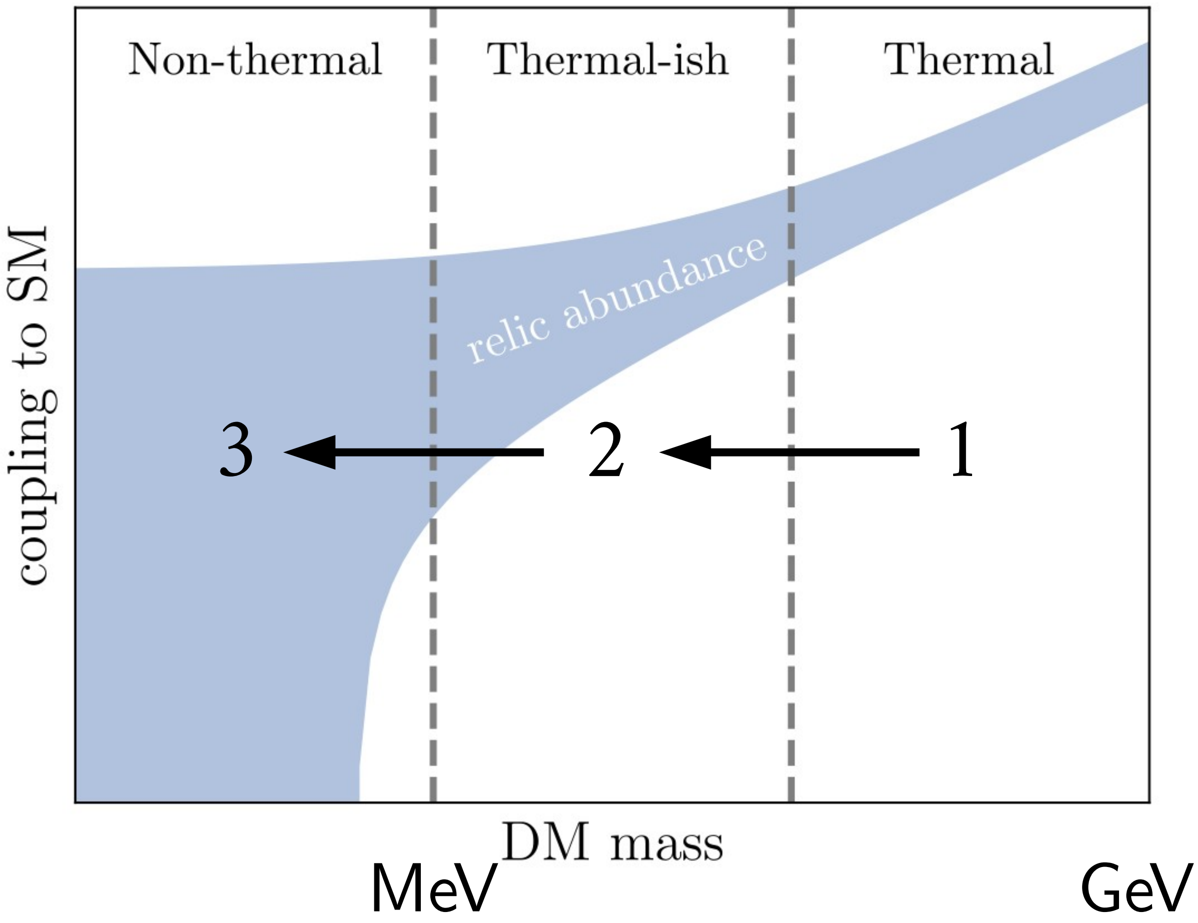
Nikita Blinov

October 6, 2020

Snowmass CPM #108

Outline

Sub-GeV DM candidates can be **roughly** categorized as



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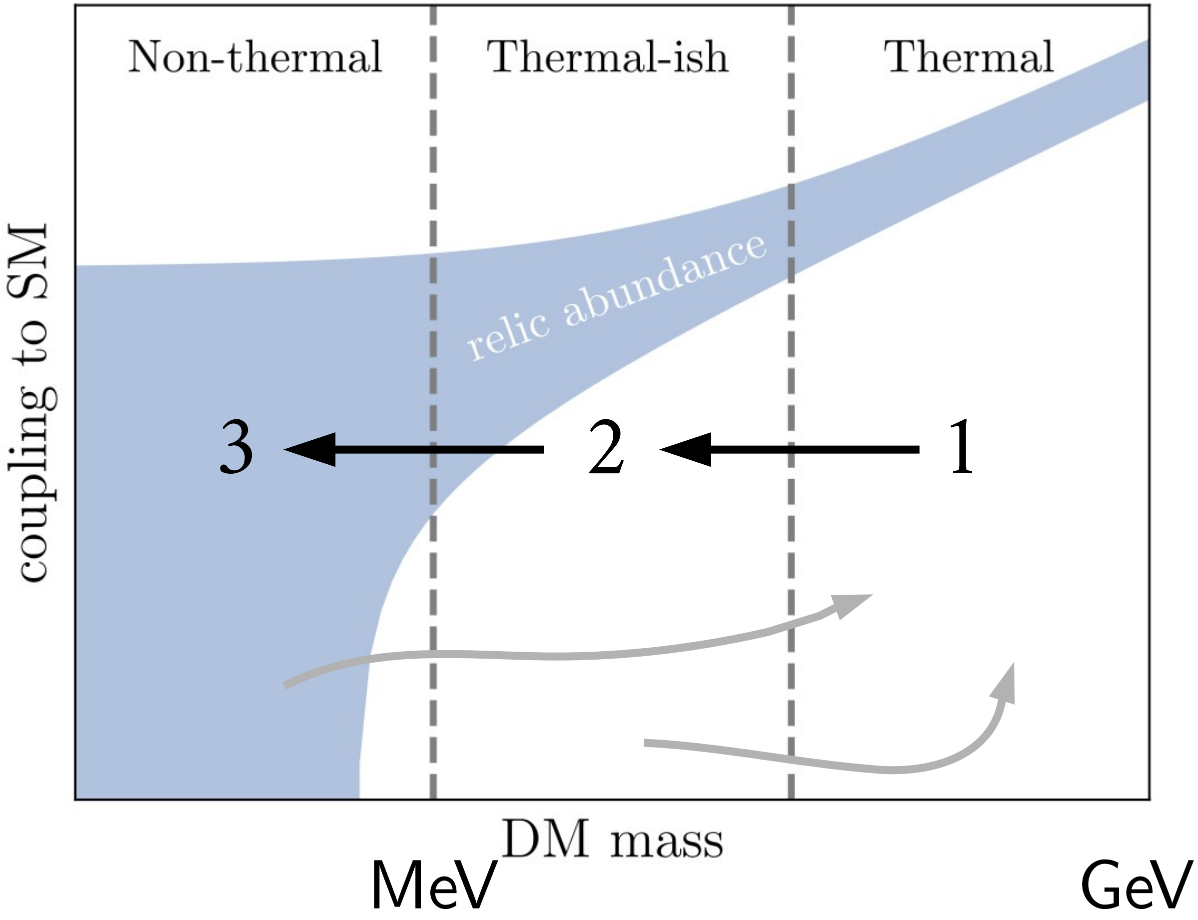
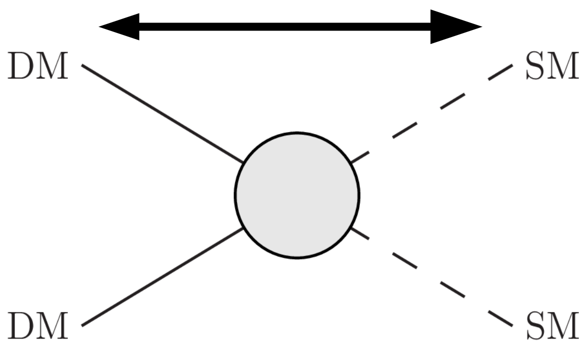


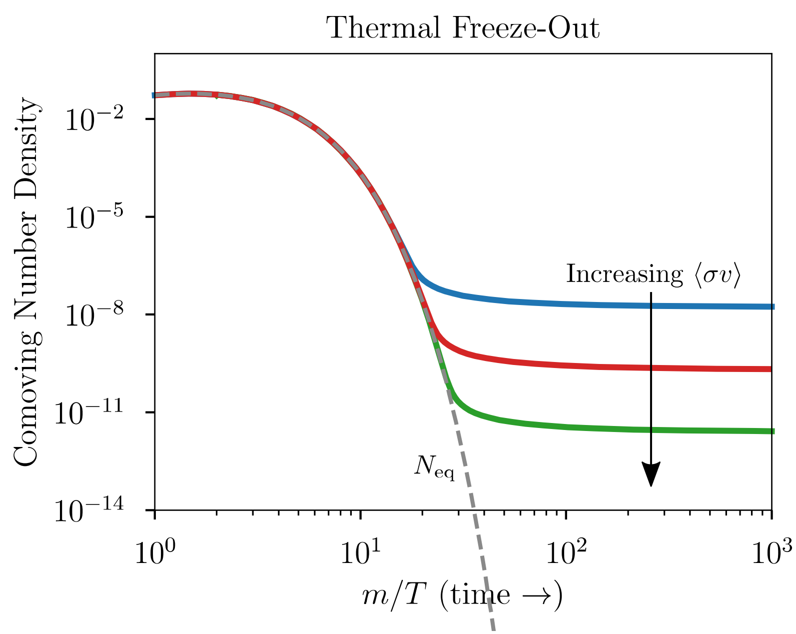
Thermal Dark Matter

DM particles were in kinetic and chemical equilibrium with the SM at early times:

$$T_\chi = T_{SM}$$

$$n_\chi = \int \frac{d^3p}{(2\pi)^3} e^{-(E-\cancelto{0}{\mu})/T_{SM}}$$





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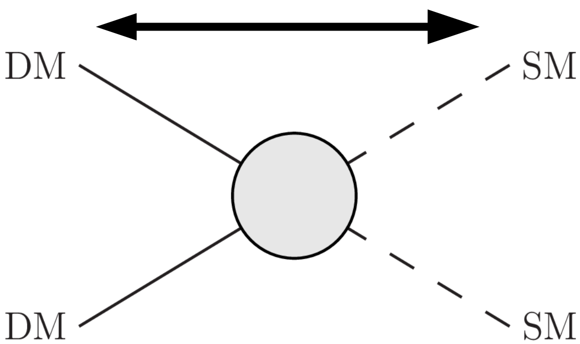

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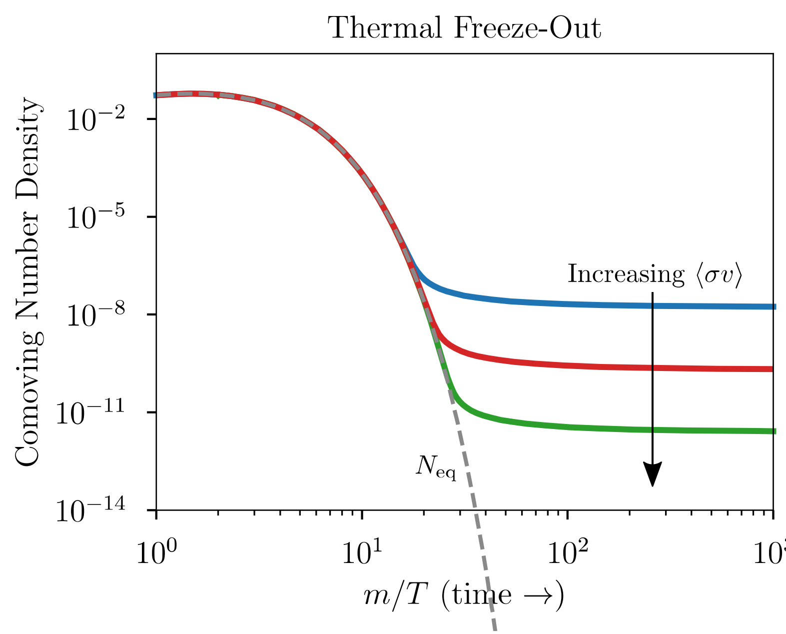

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$$m_\chi \sim \alpha_{\rm eff} \underbrace{(T_{\rm eq} M_{\rm Pl})^{1/2}}_{\text{100 TeV}}$$

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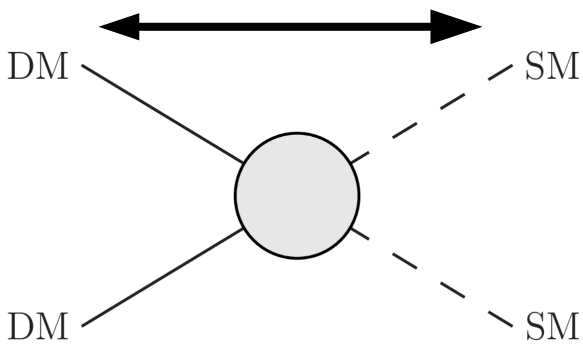

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Advantages of thermal DM

1) Insensitive to UV/initial conditions

2) **Interactions with SM required**

3) Finite mass range

Annihilation Channels

A large but finite set of freeze-out channels possible

Available final states: ν, γ, ℓ, q

Theoretical Considerations: Only a few *low-dimensional*, *gauge-invariant* connections to BSM

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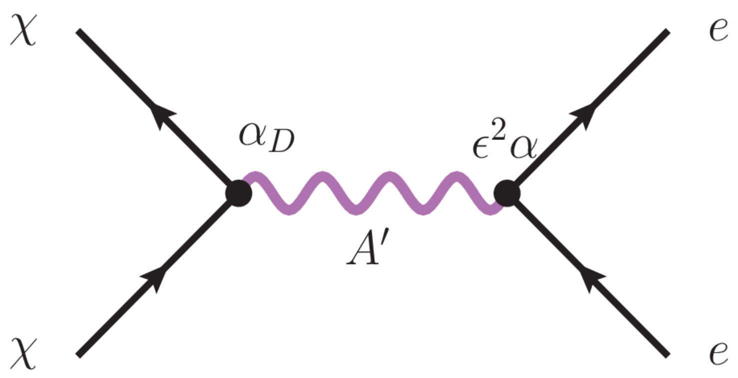
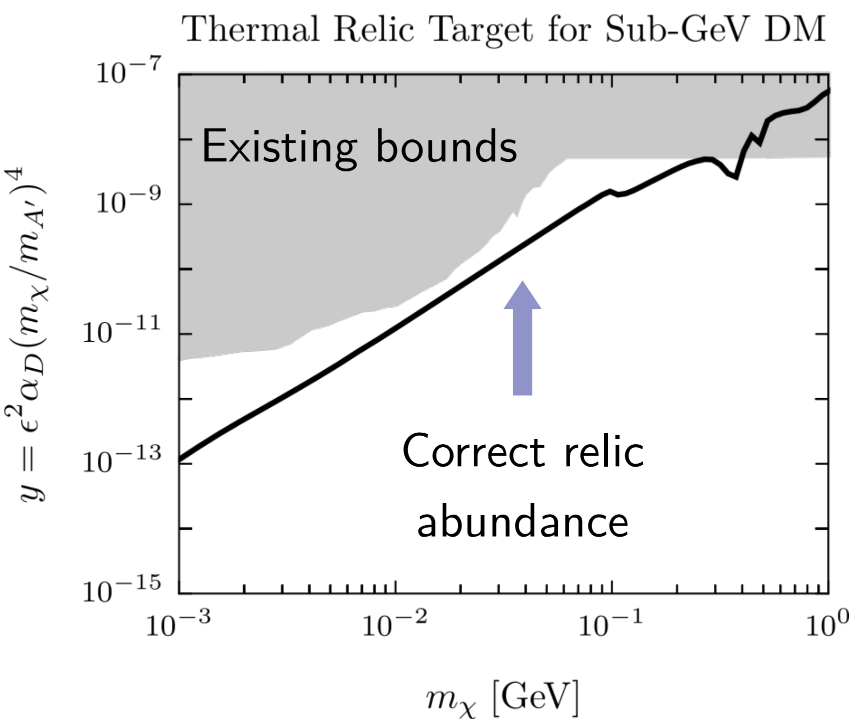
$A'_\mu J^\mu_{\rm SM}$	Dark vectors $\Rightarrow$	Coupling to conserved currents
$\lvert H\rvert^2\phi^2$	Higgs portal scalar $\Rightarrow$	Coupling to fermions
LHN_R	Right-handed neutrino $\Rightarrow$	Coupling to neutrinos
$aF_{\mu\nu}\widetilde{F}^{\mu\nu}$	Pseudo-scalar $\Rightarrow$	Coupling to electromagnetism
$\vdots$		

Pospelov, Ritz and Voloshin '07++

Thermal Example 1: Dark Photon

Dark matter coupled to the dark photon can annihilate directly into SM particles





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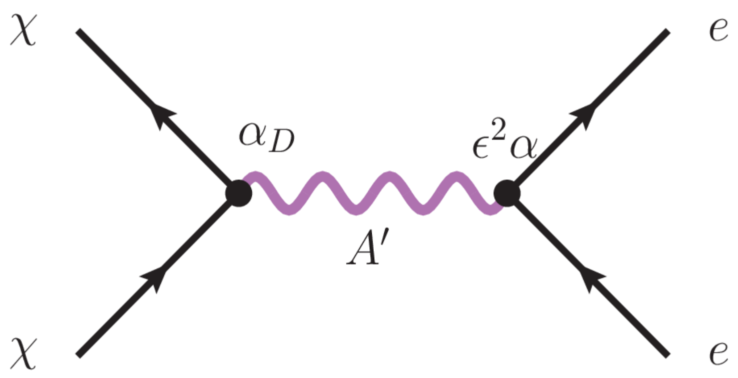

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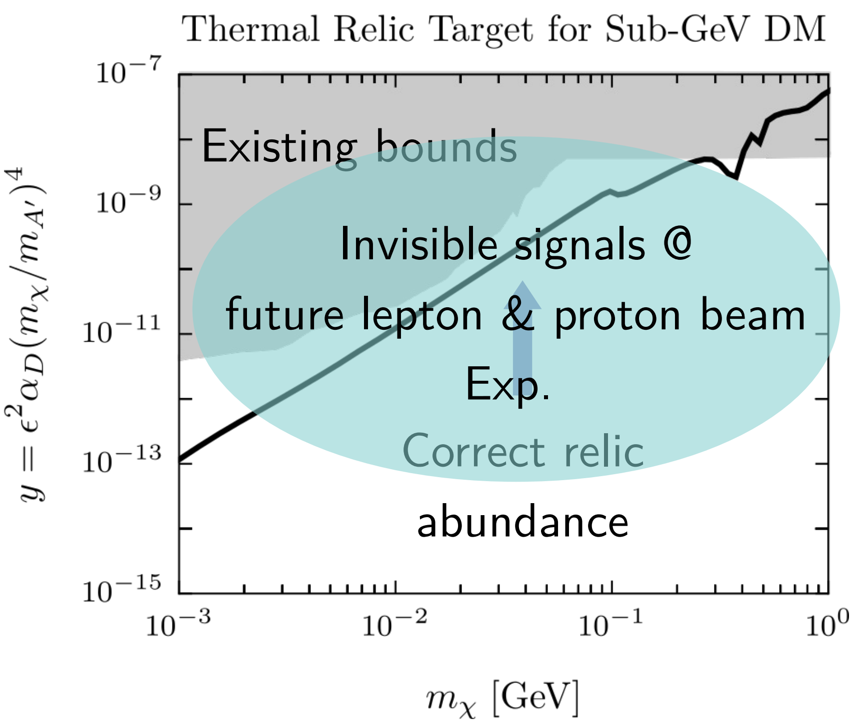
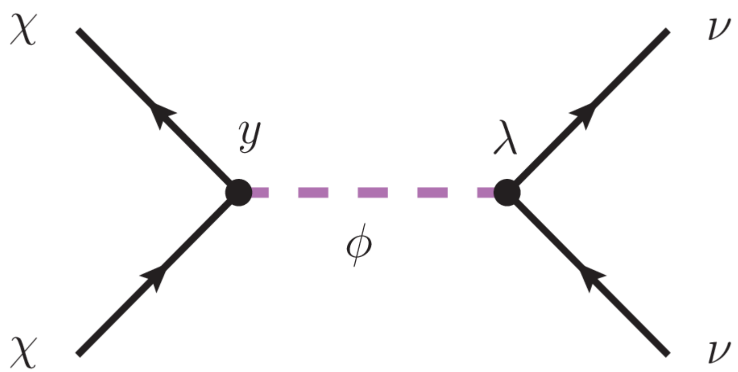


Several well-motivated thermal targets within reach of future experiments

Thermal Example 2: Neutrinophilic DM

Similar targets present for neutrino-coupled DM

$$y\phi\chi^2 + y' LHN + (M_N + \lambda\phi)N^2$$



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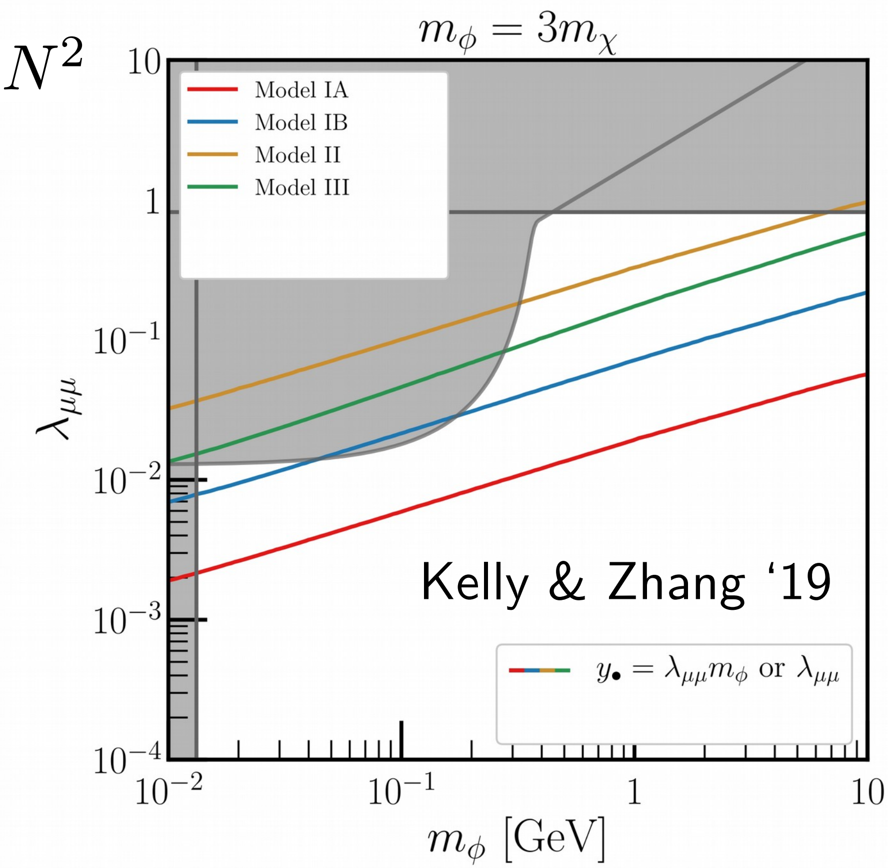
Batell *et al* '17

Kelly & Zhang '19



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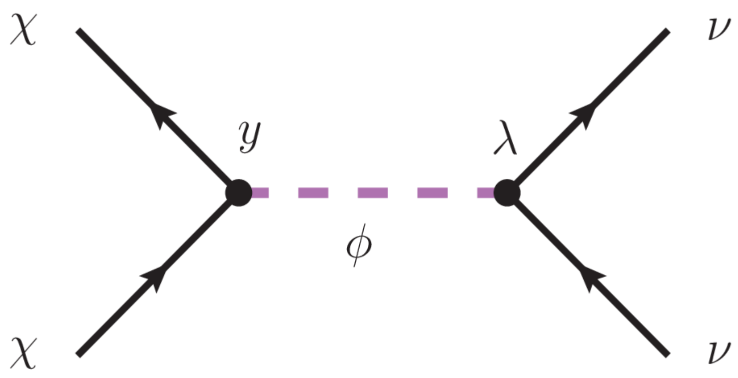

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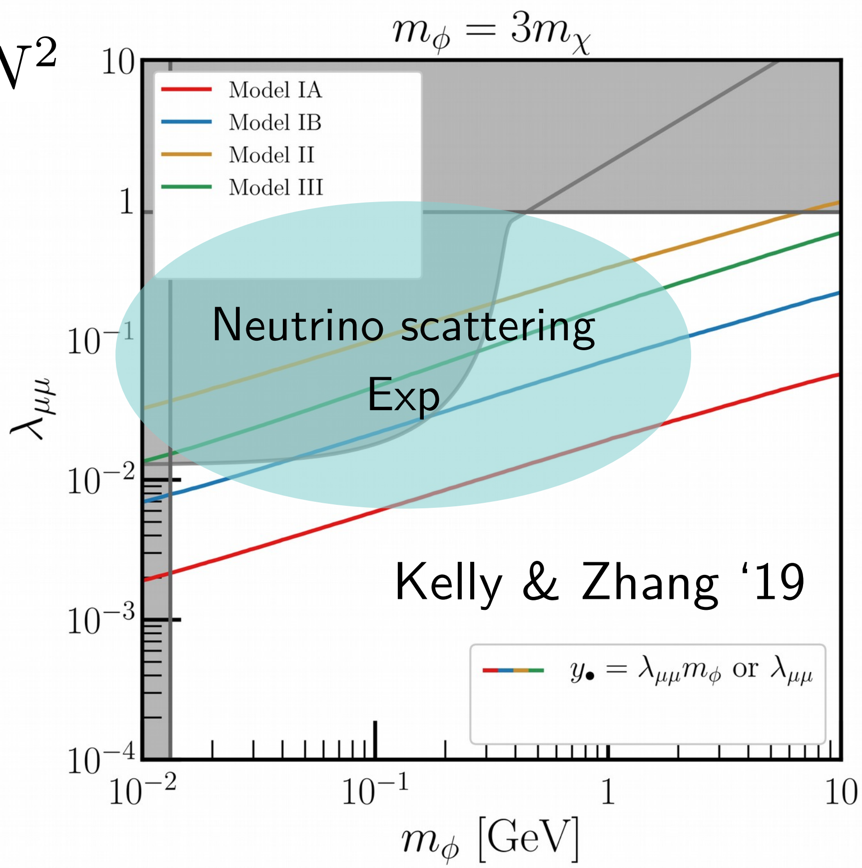

Probed by neutrino beams, rare decays and sterile searches

Thermal-ish Dark Matter

- DM particles were in kinetic but not chemical equilibrium with the SM

Hochberg *et al* '14

$$T_\chi = T_{SM}$$

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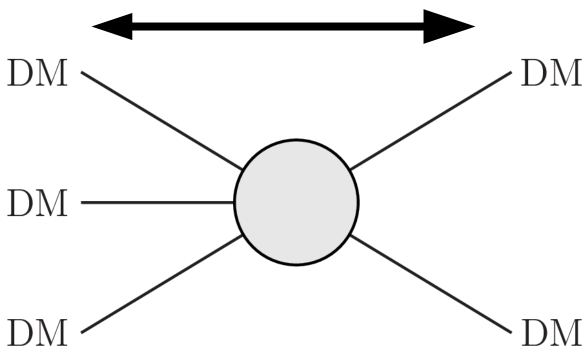
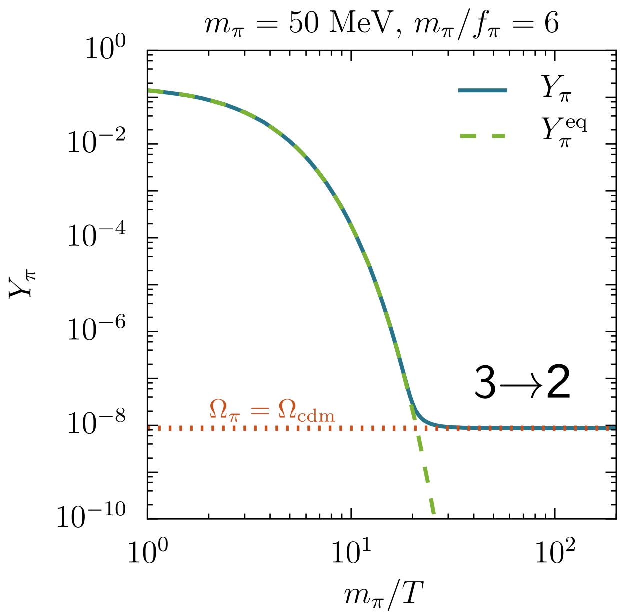
Only DM-number-changing process





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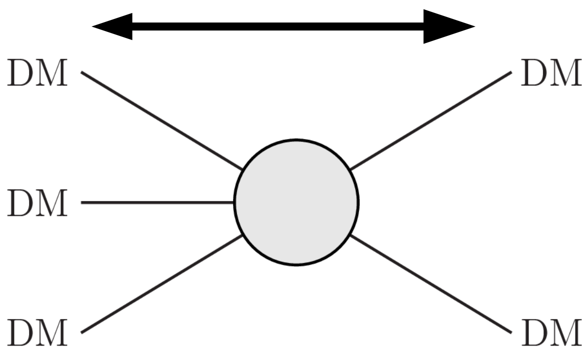

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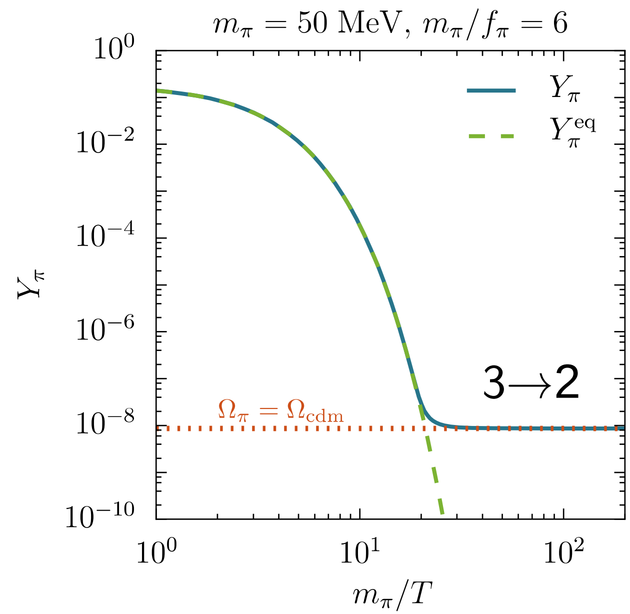

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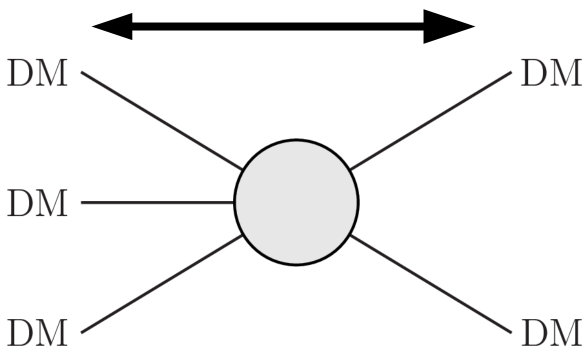
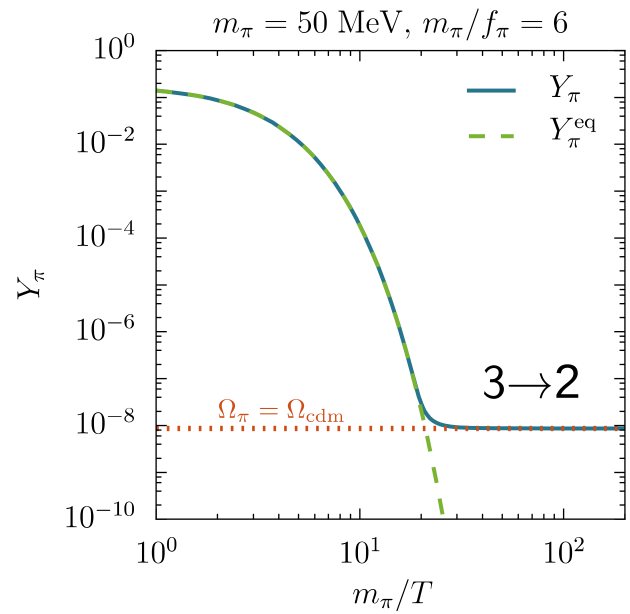


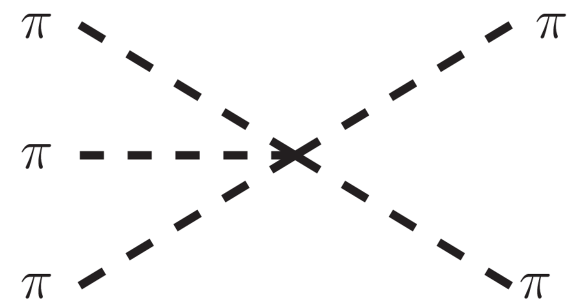


DM abundance determined by DS dynamics, but **requires** kinetic equilibrium with SM

Confining Dark Sectors

QCD-like models naturally realize 3$\to$2 freeze-out via

$$\frac{N_c}{240\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right)$$



1411.3727 (Hochberg *et al* '15)++

Kinetic equilibrium with SM required to avoid DM overproduction. Many ways (interactions) to do this:

dark photons, ALPs, Higgs portal,...

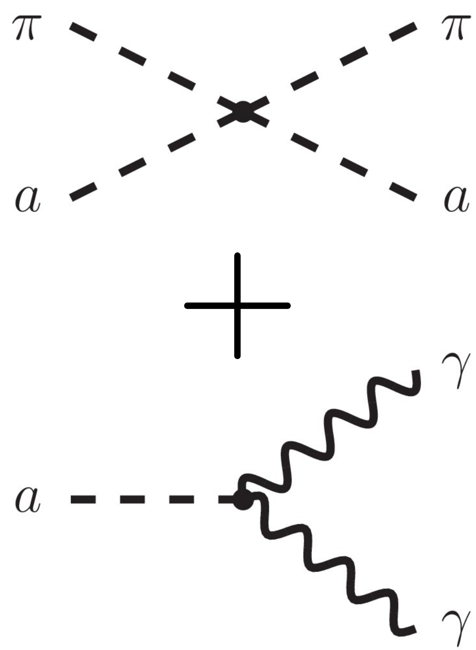
Hochberg, Kuflik & Murayama '15
Berlin, NB, Gori, Schuster & Toro '18
Katz, Salvioni & Shakya '20

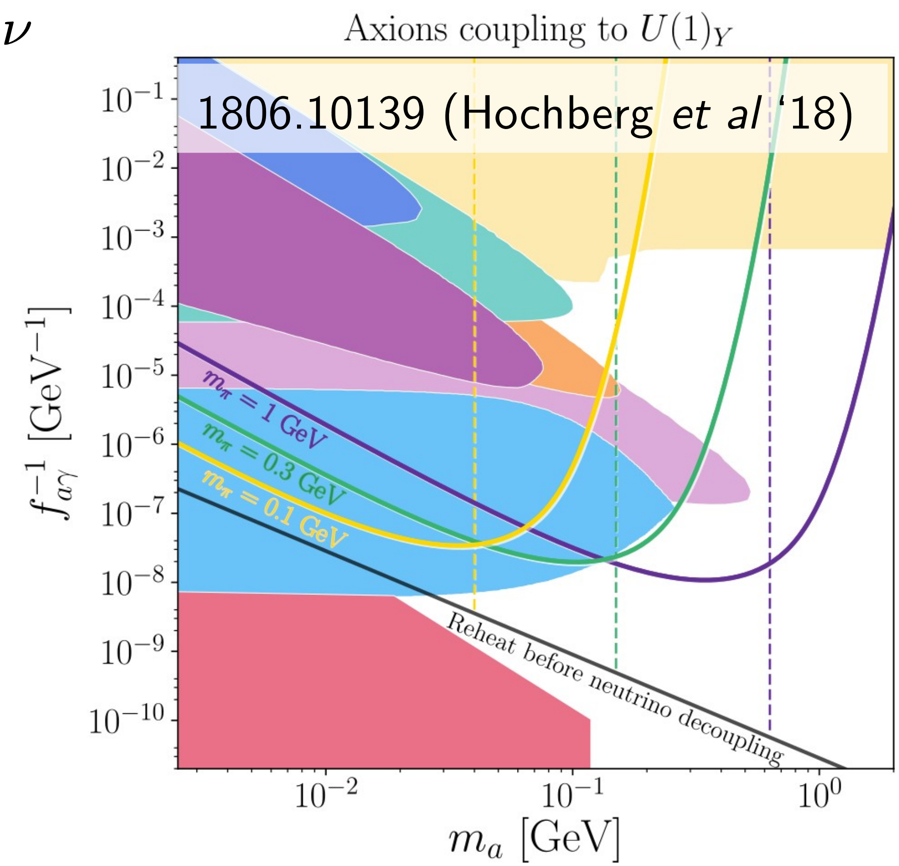
Choi *et al '17*

Hochberg *et al '18*

Kinetic Equilibrium With ALPs

$$\mathcal{L} \supset \kappa a^2 \pi^2 + \frac{a}{f_{a\gamma}} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$





Requiring that this is rapid enough gives **lower** bound on $f_{a\gamma}^{-1}$

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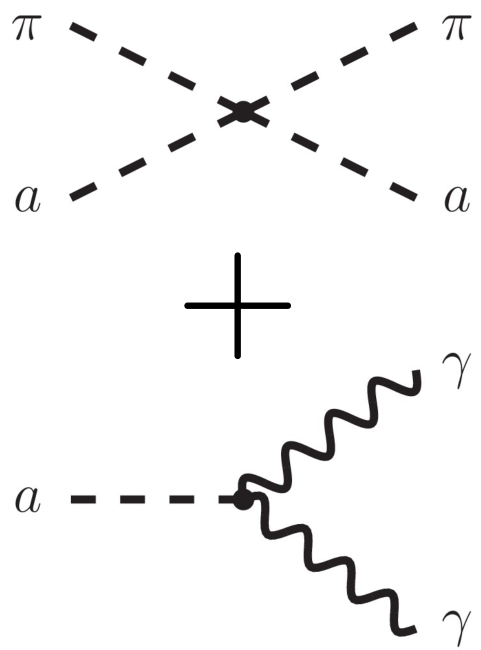

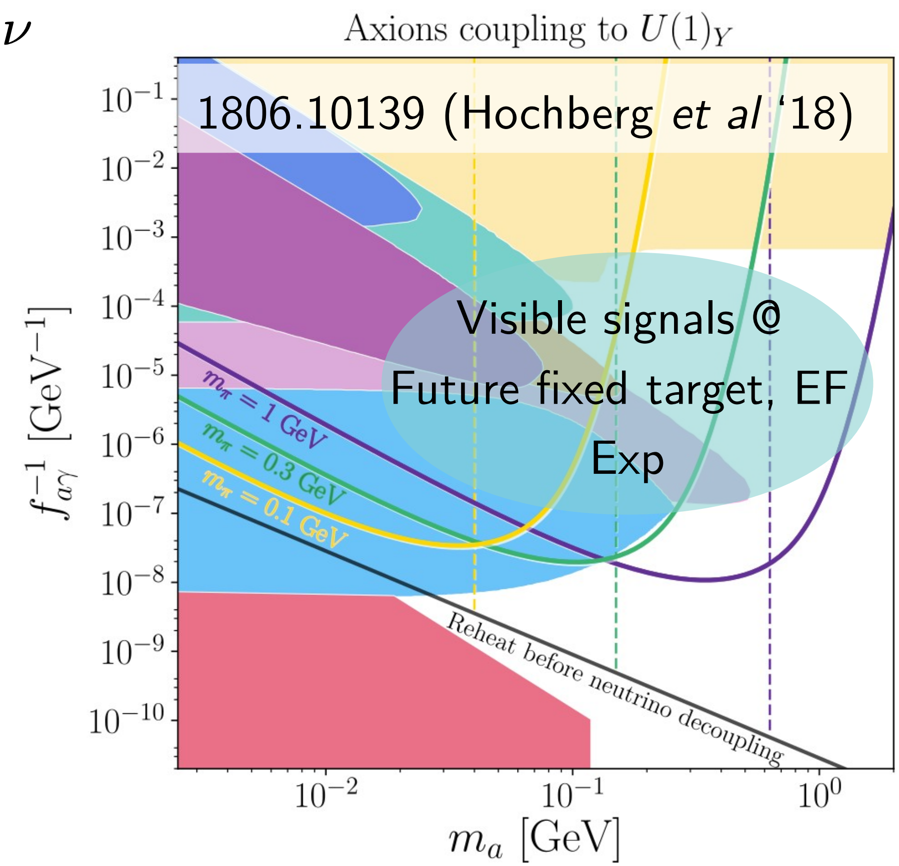

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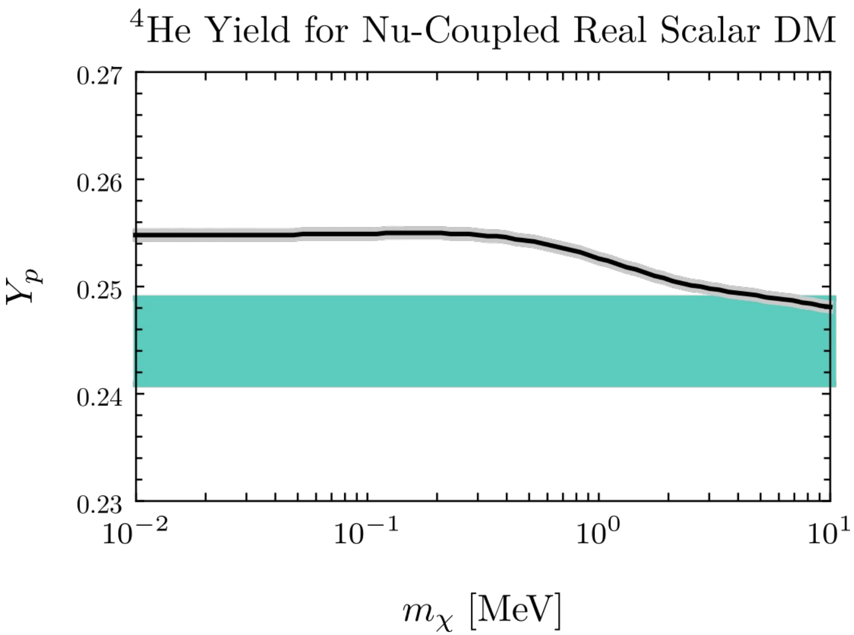
Dark Matter Below an MeV

- In thermal(-ish) models at early times

$$\rho_{\rm DS} \sim \rho_\gamma \sim T^4$$

DM+associated particles



- If DS lighter than a few MeV

$$H(T) \propto \sqrt{\rho_{\rm SM} + \rho_{\rm DS}} \quad \eta_b = \frac{n_b}{n_\gamma}$$

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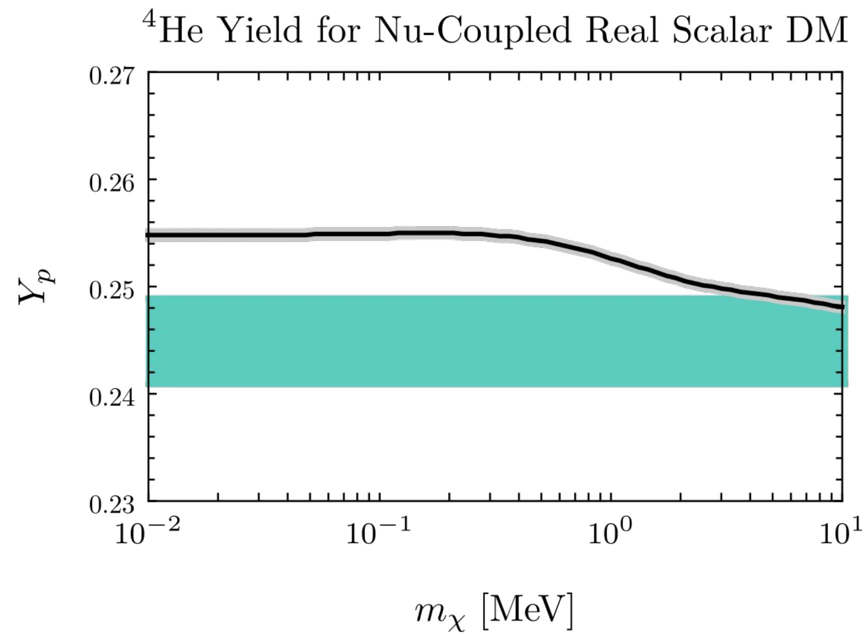

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Wrong predictions for

$$^4\text{He, D}$$

abundances!

See, e.g., 1910.01649 (Sabti *et al* '19)

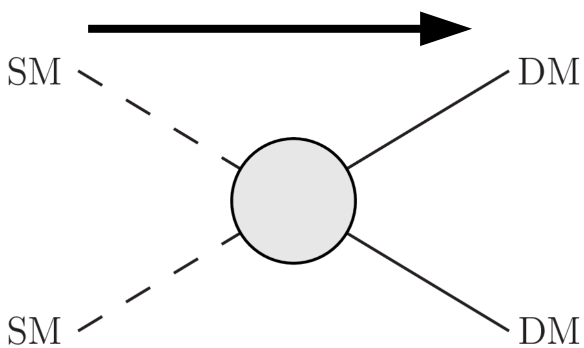
DM below an MeV could not have been in equilibrium with SM just before nucleosynthesis

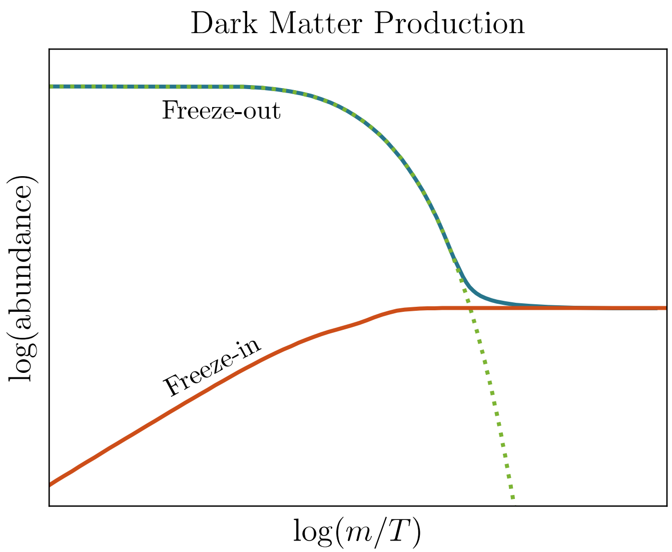
Non-Thermal Dark Matter

DM particles were *never* in kinetic or chemical equilibrium with the SM

$$T_\chi \neq T_{SM}$$

$$n_\chi = \int \frac{d^3p}{(2\pi)^3} f_\chi(E)$$





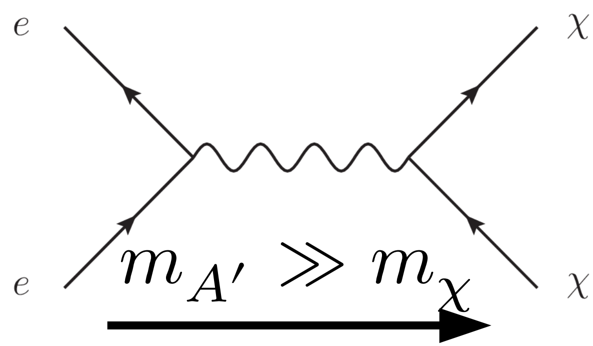
$$n_{\rm SM}\langle\sigma v\rangle \ll H(T)$$

$$\Omega_\chi \propto \int_{t_i} dt\, n_{\rm SM}\langle\sigma v\rangle$$

Dodelson & Widrow '93; Hall *et al* '09

Example 1: Freeze-in With a Massive A'

Freeze-in typically requires tiny couplings



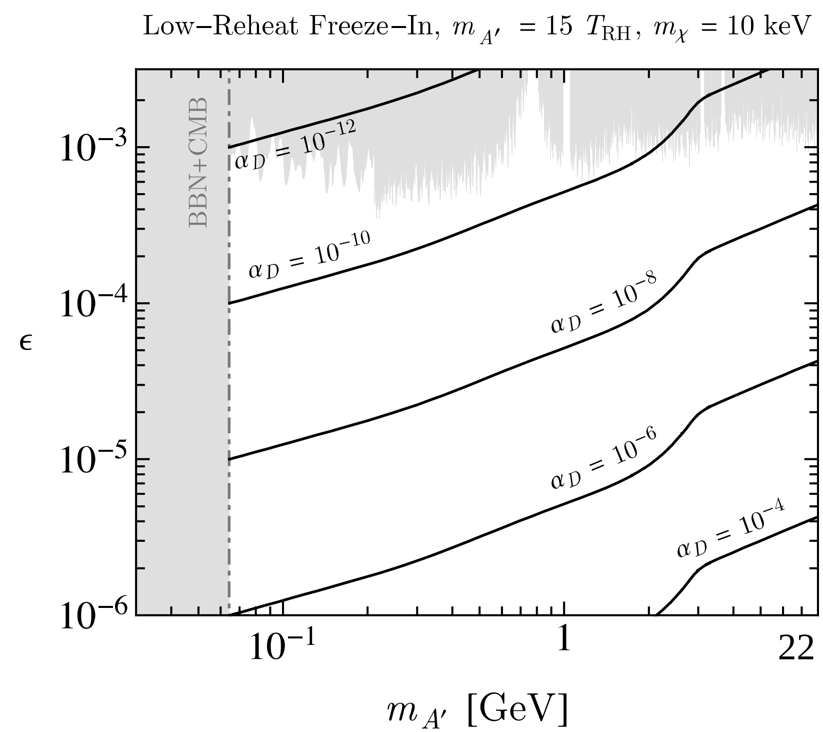
$$\epsilon^2 \alpha_D \sim 10^{-22} \left(\frac{m_{A'}}{m_\chi} \right)$$

Berlin, NB, Krnjaic, Schuster & Toro '18

Accelerator-accessible signals possible if

$$\alpha_D \lll 1$$

Visible and invisible mediator decays



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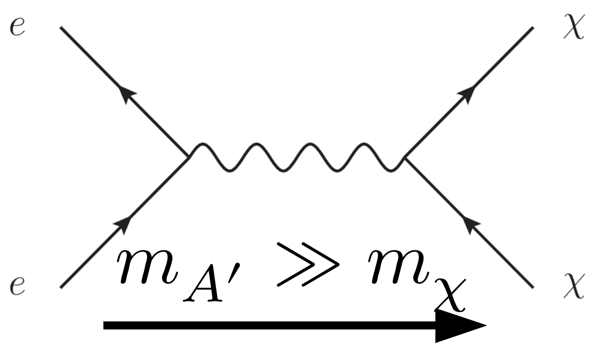

$m_{A'} \gg m_\chi$

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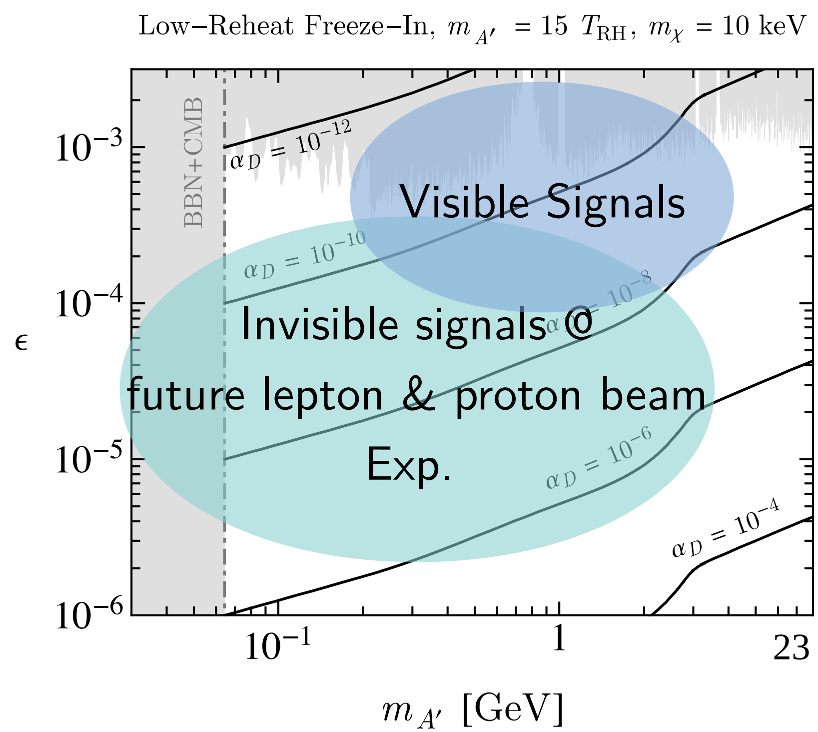


Outlook

- Cosmological production of DM can identify "preferred" regions in DM mass and coupling

- Theoretical principles and SM spectrum further constrain possible interactions and signals

- Even nightmare-ish models (e.g., neutrinophilic couplings and freeze-in) potentially accessible

Wide range of accelerator techniques needed to test keV – GeV DM across a variety of cosmological histories

Thank you!

Appendix

Dark Matter from a Dark Sector

Accelerator-accessible DM models rely on additional particles to realize early-universe production

- Mediator particles that couple to SM and DM
- Excited DM states
- DM scattering partners
- ...

A rich set of DM-related signals is possible

Invisible, semi-visible, visible

A broad experimental program is required!

Advantages of Thermal DM

1) Insensitive to UV/initial conditions

thermodynamics and cosmological evolution determine abundance

2) **Interactions with SM particles required**

motivates specific regions in model parameter space to target with experimental searches

3) Finite mass range

less room for DM to hide

Thermal DM Caveats

Not all models of thermal DM predict SM coupling as a function of DM mass. Examples include

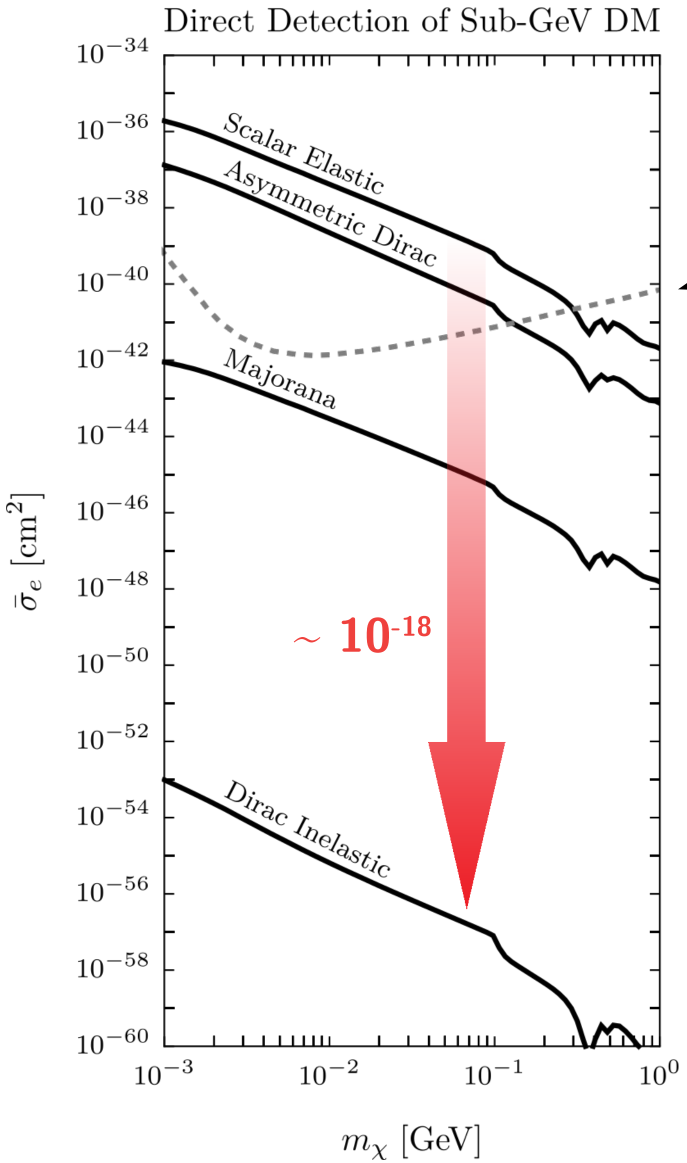
1) Secluded DM: DM mass $<$ mediator mass. No target SM coupling because abundance determined by DS interactions alone

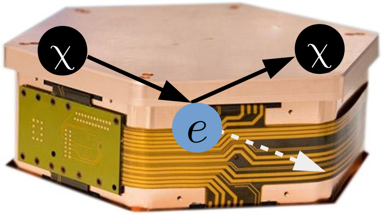
Examples include 1812.05103 (Batell et al '18)

2) Resonant annihilation: if mediators mass close to twice the DM mass, tiny SM couplings can still lead to correct abundance

See, e.g., 1707.03835 (Feng and Smolinksy '17)

Advantages of Accelerator Searches



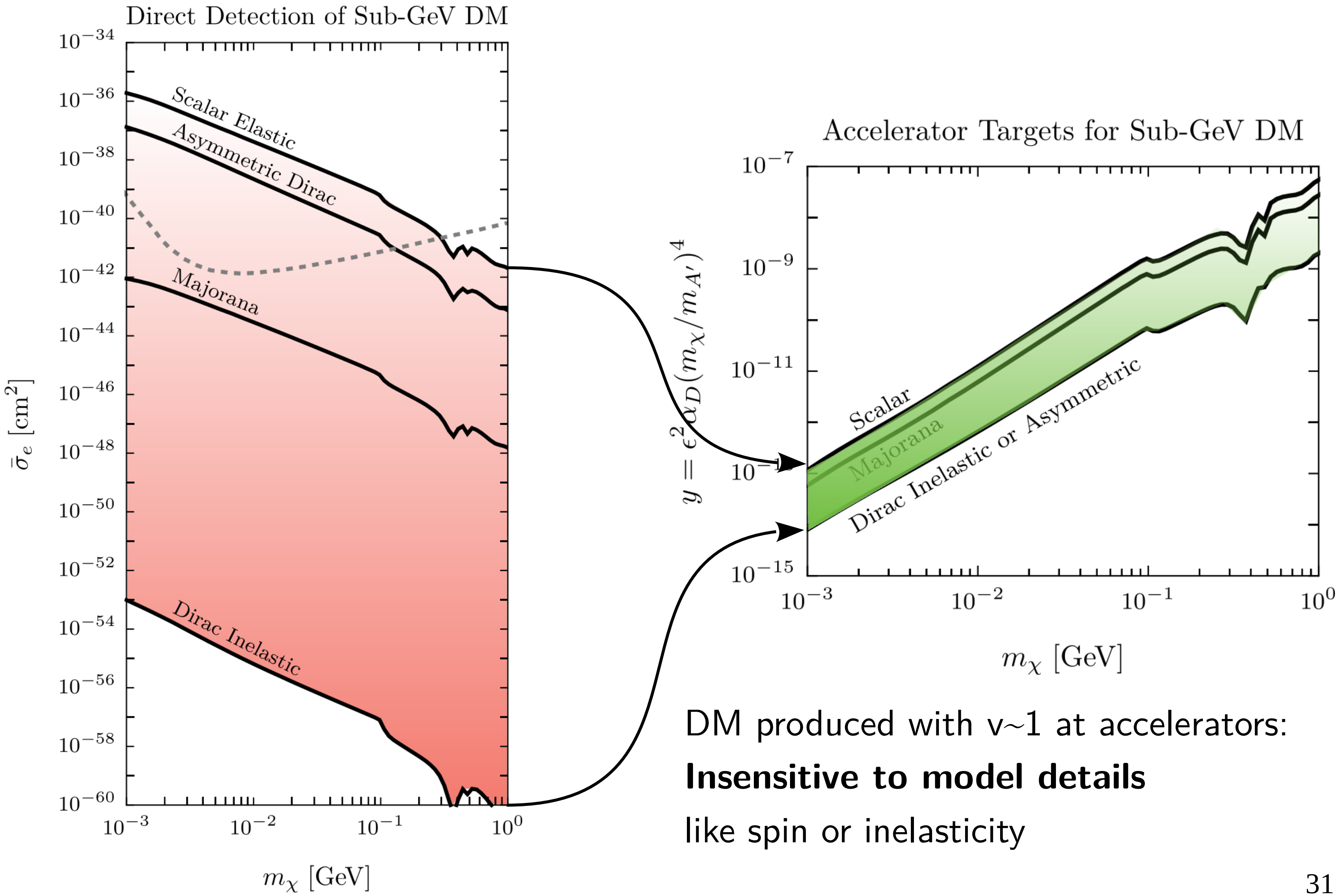


SuperCDMS SNOLAB

Direct detection strongly sensitive to possible DM velocity dependence in scattering rates:

Challenging to cover all thermal targets!

Advantages of Accelerator Searches



DM produced with v~1 at accelerators:

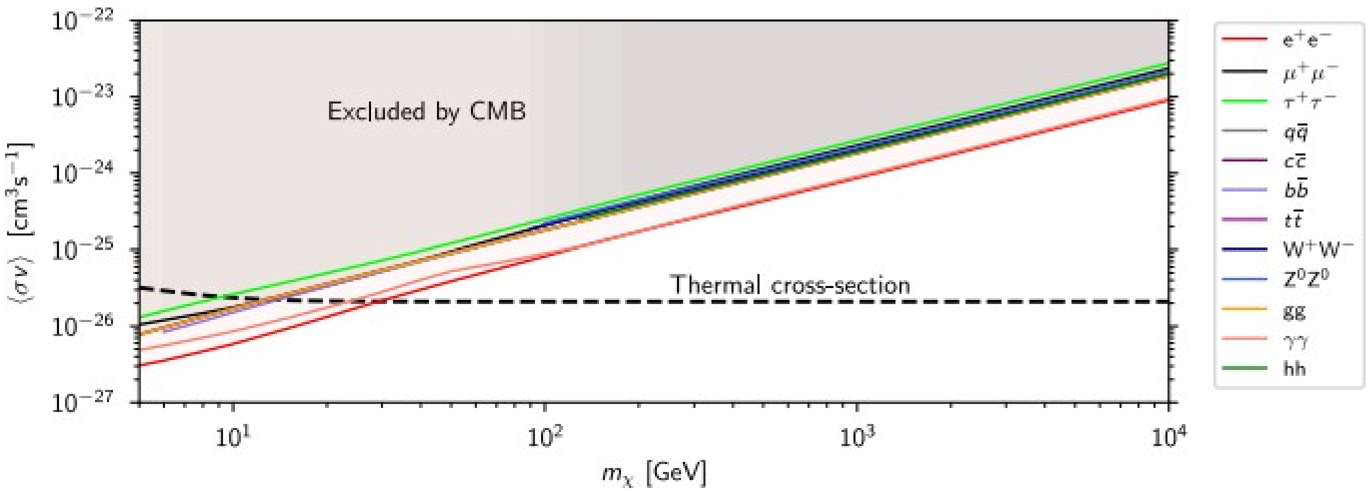
Insensitive to model details

like spin or inelasticity

Indirect Searches

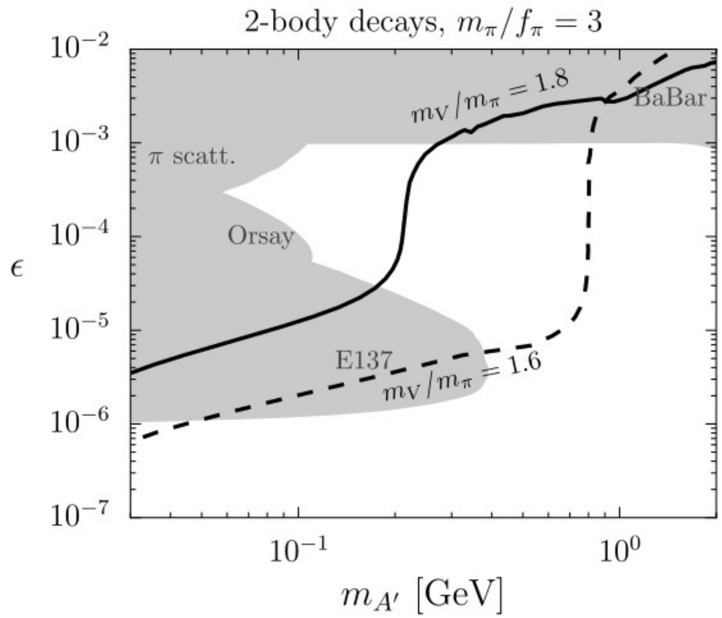
Look for annihilation products today: but CMB bounds preclude an indirect detection signal

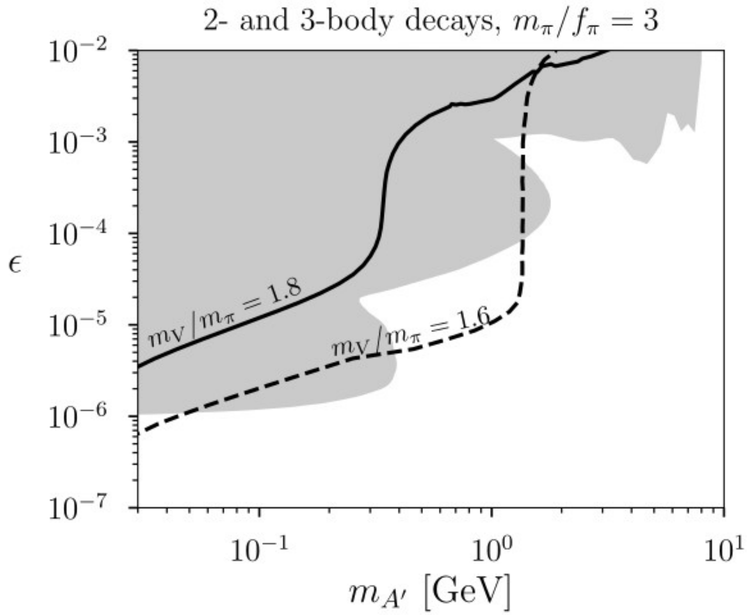
If residual annihilation continue after recombination: ionize neutral hydrogen and distort the CMB!
E.g. 100 MeV DM particle annihilating to electrons has enough energy to dissociate 10^7 H atoms!



Late-time annihilations must be suppressed – no indirect detection signal

Dark Photon-Coupled SIMPs

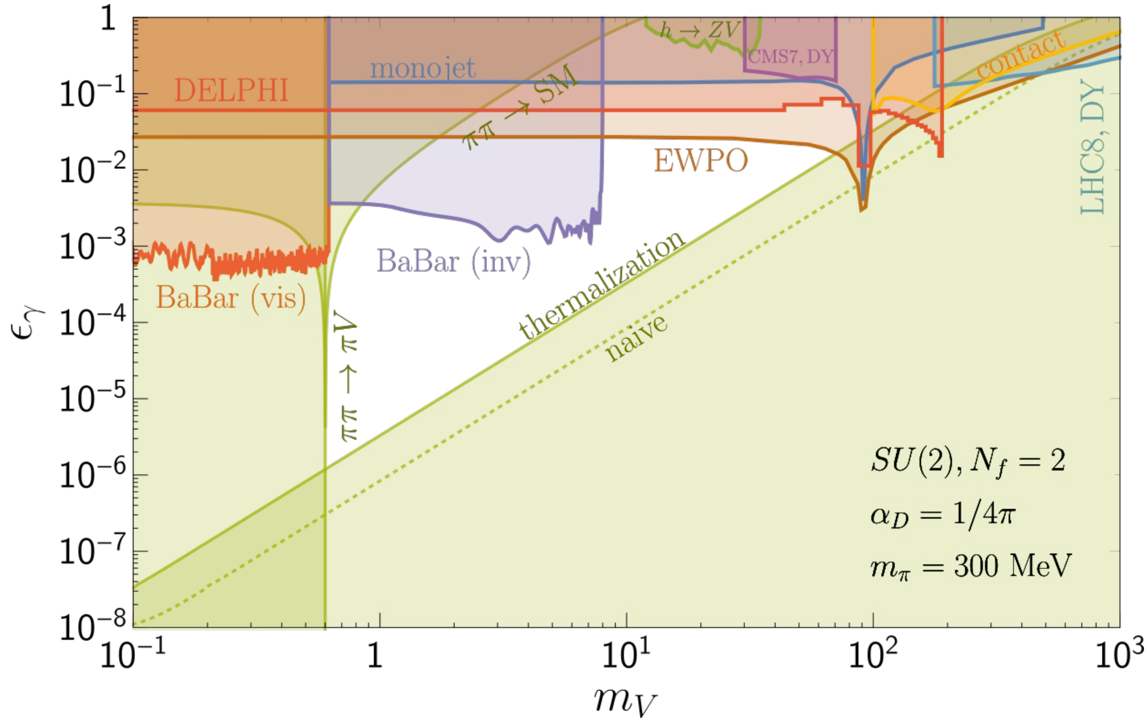




Berlin, NB, Gori, Schuster & Toro '18

Heavier Mediators

- Heavier mediators cannot be produced at fixed target experiments, but may be accessible at LHC

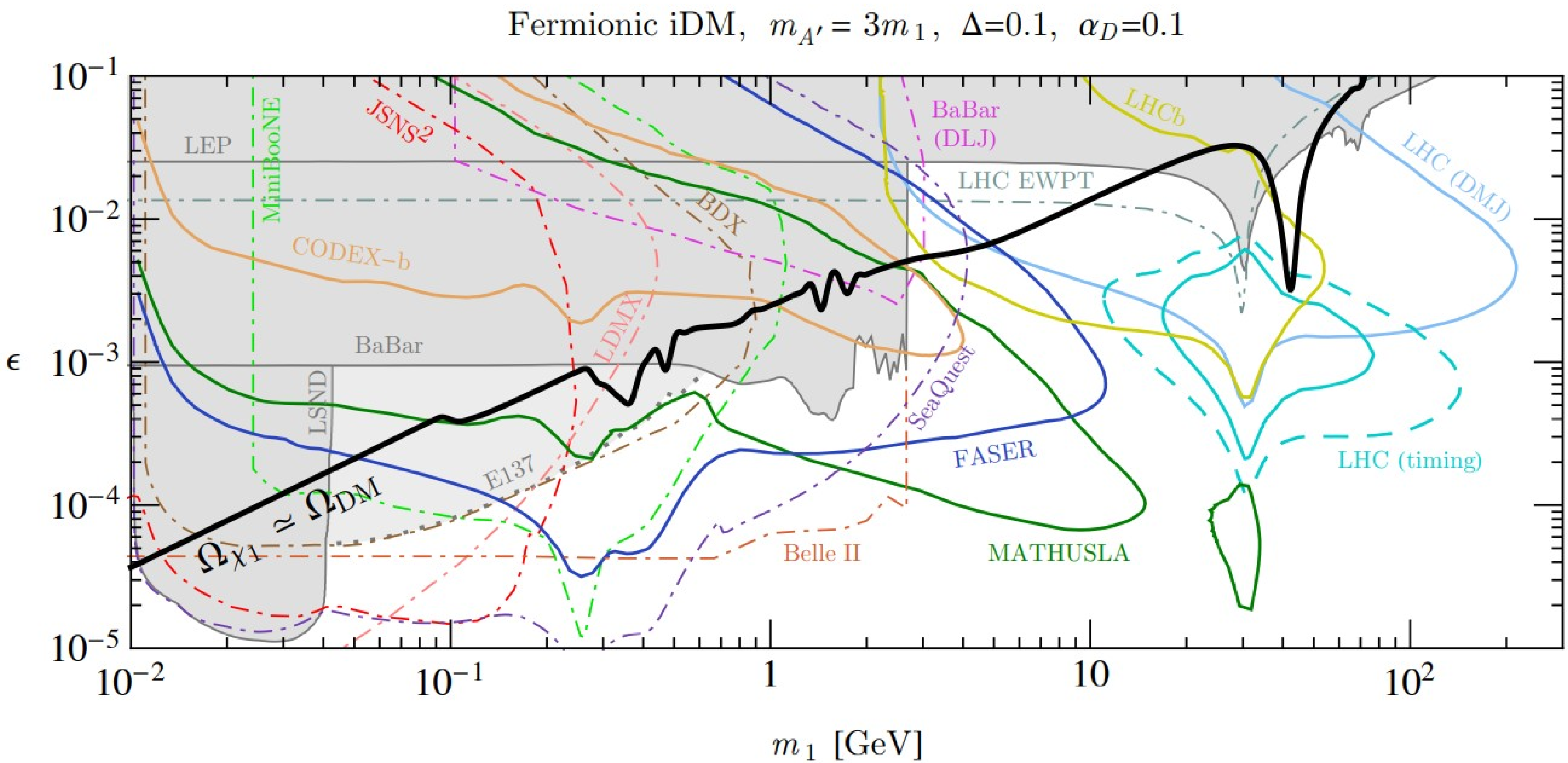


Hochberg, Kuflik & Murayama ‘15

Katz, Salvioni & Shakya ‘20

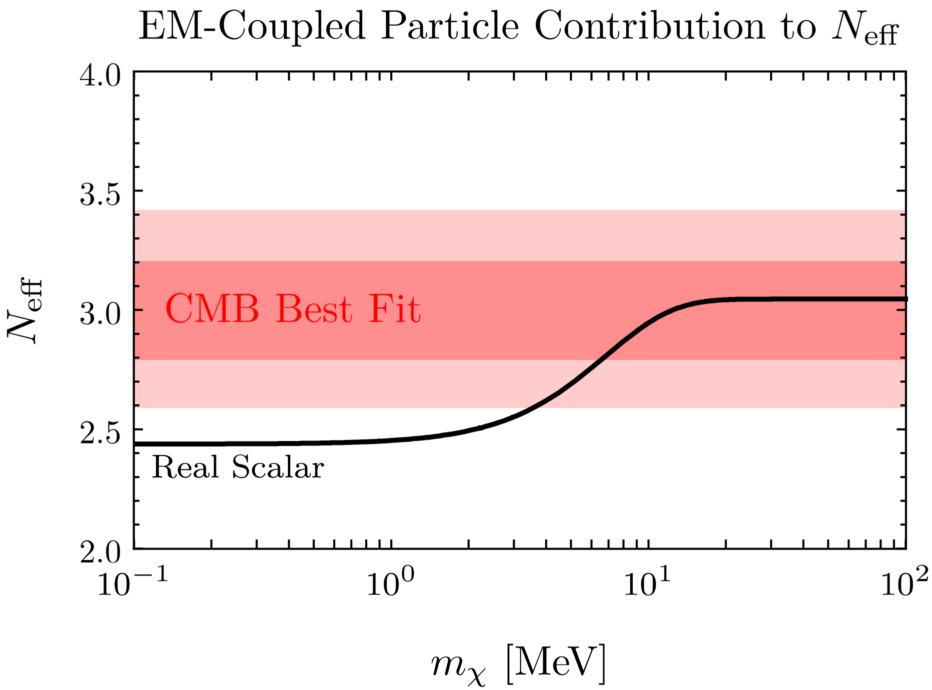
Heavier Dark Matter

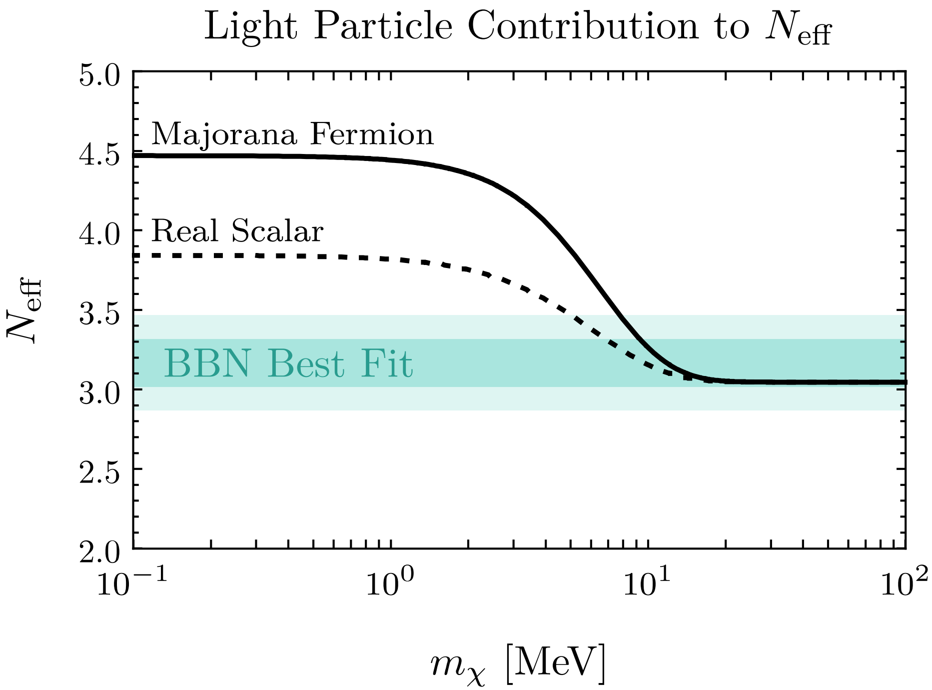
- LHC-based experiments can probe heavier DM



Berlin & Kling '18

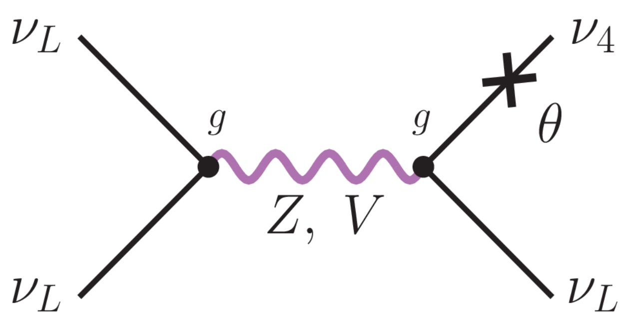
Light Dark Sectors and BBN





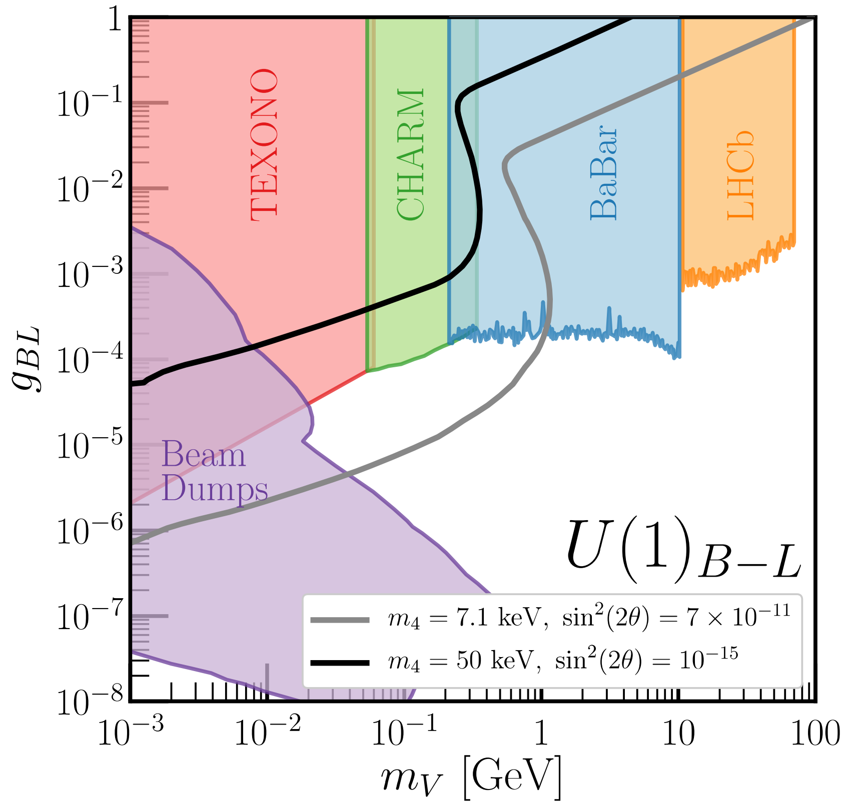
Example 2: Sterile Neutrinos

Sterile neutrinos from nu-self-interactions via mixing



BSM self-interaction necessary for sufficient abundance

Kelly *et al* '20



See, e.g., de Gouvêa *et al* '20

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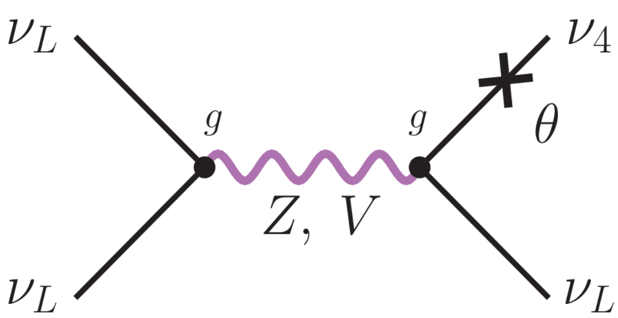
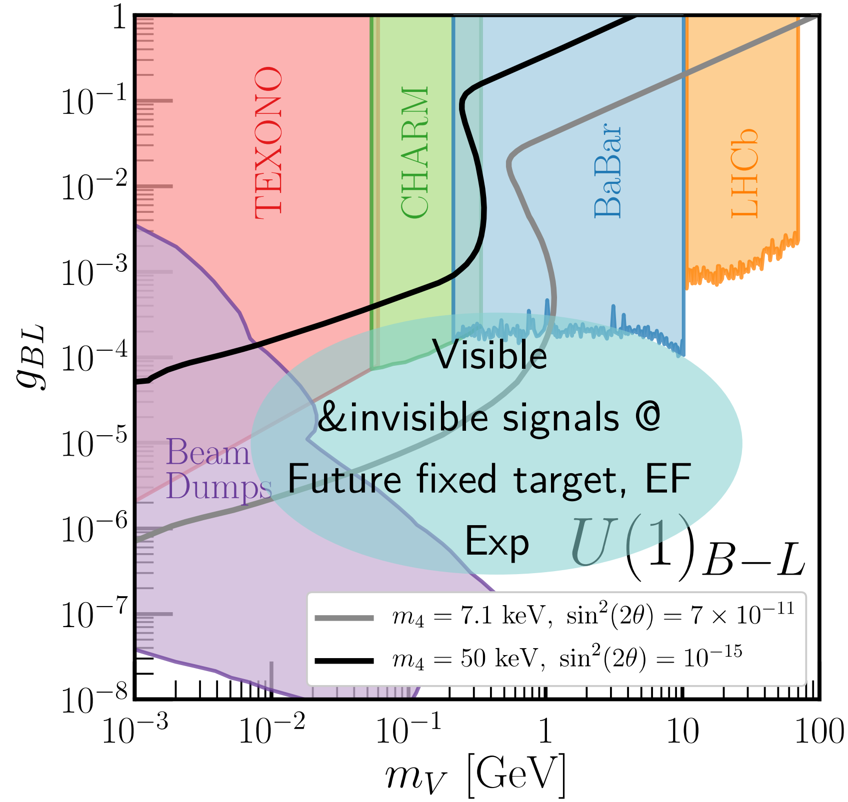


BSM self-interaction necessary for sufficient abundance

Kelly *et al* ‘20



See, e.g., de Gouvêa *et al* ‘20

Kelly *et al* ‘20